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Temperature dependence of the average electron-hole pair creation energy in $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$

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The temperature dependence of the average energy consumed in the creation of an electron-hole pair in the wide bandgap compound semiconductor $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ is reported following X-ray measurements made using an $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ photodiode diode coupled to a low-noise charge-sensitive preamplifier operating in spectroscopic photon counting mode. The temperature dependence is reported over the range of 261 K–342 K and is found to be best represented by the equation $\varepsilon_{\text{AlGaAs}} = 7.327 - 0.0077T$, where $\varepsilon_{\text{AlGaAs}}$ is the average electron-hole pair creation energy in eV and T is the temperature in K. © 2013 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1063/1.4804989>]

The compound semiconductor $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ has received attention as a detector material for use in soft X-ray spectroscopy instruments which need to operate at high temperature ($\gg 20^\circ\text{C}$).^{1–13} At high temperatures, the wide bandgap of $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ (2.09 eV (Ref. 14)) leads to a thermally generated leakage current lower than that which would be present in a silicon detector of the same design. $\text{Al}_x\text{Ga}_{1-x}\text{As}$ also benefits from being lattice matchable to GaAs substrates; there is much existing GaAs fabrication technology and experience available which is readily transferable to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, further supporting its development.

Development of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ X-ray detectors has, until recently, been impeded by a lack of knowledge about many of its material properties and their temperature dependences. For example, the electric field dependence of the impact ionization coefficients at room temperature has been reported for $x = 0.15, 0.3, 0.6,$ ¹⁵ $x = 0.2, 0.4,$ ¹⁶ and $x = 0.8,$ ¹⁷ but only limited data is available about their temperature dependences, with reports for $x = 0.2, 0.4,$ ¹⁶ $x = 0.6,$ ¹⁸ and $x = 0.8$ (Ref. 12) at very few electric field strengths. Also, the average energy consumed in the creation of an electron-hole pair, commonly called the electron-hole pair creation energy, ε , in $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ has only recently been reported at room temperature for X-rays,¹⁹ and there is currently no report of the Fano factor, F , in $\text{Al}_x\text{Ga}_{1-x}\text{As}$. Knowledge of ε and F and their temperature dependences is important since they determine the statistically limited spectral resolution of an X-ray detector for a given incident photon energy, E

$$\text{FWHM}[\text{eV}] = 2.355\sqrt{FE\varepsilon}. \quad (1)$$

In this paper, the temperature dependence of the electron hole pair creation energy in $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ is determined and reported for the temperature range 261 K–342 K from X-ray measurements made using an ^{55}Fe radioisotope source and

an $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ photodiode coupled to a custom low-noise charge-sensitive preamplifier.

To measure the temperature dependence of the electron-hole pair creation energy, ε , the same unpassivated $\text{p}^+\text{-i-n}^+$ circular (100 μm radius) mesa $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ diode, as was used in the relative measurement of ε in $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ at room temperature,¹⁹ is used. The layer properties of the molecular beam epitaxy (MBE) grown wafer from which this device was fabricated by photolithography are given in Table I. The thinness of the devices fabricated from this wafer (i layer thickness = 1 μm) makes them ideal for use in determining ε since there is minimal material in which there can be charge trapping, they also have low optimum operating reverse biases (10–14 V) and low leakage currents (e.g., 4.3 pA at 10 V). The device's capacitance before packaging was measured as 3.1 pF at ≥ 10 V, and their performance was found to be very stable over time; they showed no measurable variations in response over periods as long as two weeks when the operating conditions (e.g., temperature) were kept constant.

The diode was mounted in a TO-5 package and connected to a custom-built low-noise ($< 40 \text{e}^-$ rms) charge-sensitive preamplifier with a Vishay Siliconix 2N4416 Si JFET input transistor (capacitance ≈ 2 pF). A 1.2 GBq ^{55}Fe radioisotope X-ray source was positioned 3 mm above the surface of the diode. A stabilized pulse generator (model BH-1, Berkeley Nucleonics Corporation) was also connected

TABLE I. Layer properties of the $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ diodes used in this work.

Layer	Material	Thickness (μm)	Dopant	Type	Doping density (cm^{-3})
1	GaAs	0.01	Be	p	2.5×10^{18}
2	$\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$	1	Be	p	2.0×10^{18}
3 (i layer)	$\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$	1	Undoped		
4	$\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$	1	Si	n	2.5×10^{18}
5	GaAs	0.25	Si	n	2.5×10^{18}
Substrate	N^+ GaAs				

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to the test signal input of preamplifier to provide a reference by which to characterize the change in gain of the preamplifier itself. The preamplifier was connected to an Ortec 571 shaping amplifier and subsequently to an Ortec EASY-MCA-8k and personal computer. To control and vary the temperature, the diode, X-ray source, and preamplifier were placed in a dry N₂ atmosphere (giving a relative humidity of <5%) to eliminate any humidity dependent effects, inside a Design Environmental FS55-65 Temperature Test Chamber (TTC). A thermocouple was positioned inside the diode's housing as close to the diode as possible, to monitor its temperature. The diode was reverse biased at 14 V by a stabilized external power supply. Spectra were accumulated from 342 K to 261 K in 10 K steps, with three spectra accumulated at each temperature. The positions of the zero energy noise peak, the photopeak, and the peak from the pulse generator were all recorded. The start of the Multichannel Analyzer (MCA) scale was set such that the whole of the zero energy noise peak could be seen for finding the position of its centroid. Because the change in the position of the pulser peak characterizes the change in gain of the preamplifier as the temperature is varied, the change in the position of the photopeak relative to the pulse generator peak (with the scales zeroed using the zero energy noise peak) shows the change in gain (coulombs charge produced per eV of photon energy) of the Al_{0.8}Ga_{0.2}As detector. This change in gain is due to the change of ϵ_{AlGaAs} . The change of ϵ_{AlGaAs} with temperature can then be made absolute since we have previously reported ϵ_{AlGaAs} at room temperature (20 °C) using a method of relative measurement with respect to a reference GaAs detector.¹⁹ The method we use to deduce the temperature dependence of ϵ_{AlGaAs} enables a higher precision measurement to be made than if the method of Ref. 19 had simply been repeated at different temperatures since the similarity of ϵ_{AlGaAs} and ϵ_{GaAs} and the reduction in spectral resolution which results from having the GaAs and AlGaAs detectors connected to the same preamplifier at the same time, causes their respective photopeaks to overlap.¹⁹ This would have been particularly problematic at high temperatures, where the thermal leakage current is increased and the photopeaks broadened and the overlap increased. The deduced temperature dependence of the electron hole pair creation energy in Al_{0.8}Ga_{0.2}As is shown in Figure 1.

The temperature dependence of the electron-hole pair creation energy in Al_{0.8}Ga_{0.2}As (in eV) has been deduced within the temperature range 261 K–342 K and has been found to decrease with increasing temperature from 5.33 eV to 4.94 eV, with a maximum measurement error of ± 0.086 eV in each case. It can be fitted well by the linear equation

$$\epsilon_{Al_{0.8}Ga_{0.2}As} = 7.327 - 0.0077T, \quad (2)$$

where T is the temperature of the device in Kelvin. The remarkably good R^2 value (0.9942) is indicative of the high levels of charge collection efficiency (CCE) present in the device. Had there been significant incomplete charge collection, which would have adversely affected the determination of ϵ_{AlGaAs} , the data in Figure 1 would have shown significant non-linearity because of CCE's dependence on multiple temperature sensitive factors.²⁰

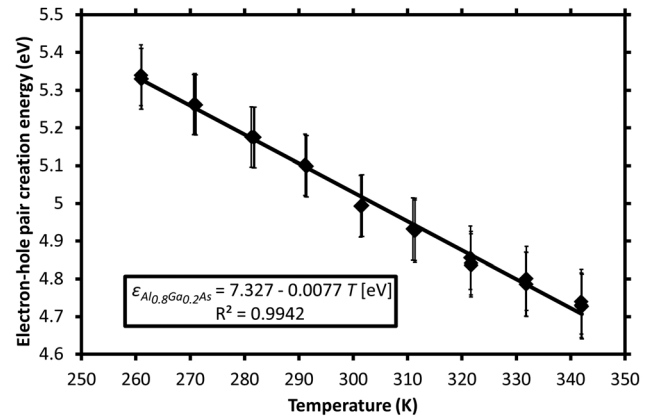


FIG. 1. The temperature dependence of the average energy required to produce an electron-hole pair in Al_{0.8}Ga_{0.2}As.

The change in average energy consumed in the generation of electron-hole pairs with temperature in Al_{0.8}Ga_{0.2}As is significant over the measured range: at 342 K it takes only $\sim 88\%$ of the energy it does at 261 K to generate an electron hole pair on average. In context, assuming a temperature invariant $F = 0.12$, this means the intrinsic spectral resolution (FWHM, Eq. (1)) at $E = 5.9$ keV of an Al_{0.8}Ga_{0.2}As detector would be 144.5 eV at 342 K compared with 135.7 eV at 261 K. Of course, the Fano factor's actual value and temperature dependence in Al_{0.8}Ga_{0.2}As still remains to be established. The gradient of the line of best fit representing the temperature dependence of the electron-hole pair creation energy in Al_{0.8}Ga_{0.2}As (-0.0077 eV/K, equivalent to -0.145% K⁻¹) measured with 5.9 keV X-rays is much steeper than that reported for GaAs (-0.00122 eV/K, equivalent to -0.029% K⁻¹) measured at 59.54 keV using ²⁴¹Am sources.²⁰ Both ϵ_{GaAs} and $\epsilon_{Al_{0.8}Ga_{0.2}As}$ have temperature gradients steeper than ϵ_{Si} which has been reported as $\sim 0.01\%$ K⁻¹ at very soft X-ray energies (50, 277, and 1800 eV) for temperatures between 308 K and 170 K.²¹ It would be interesting to compare the temperature dependence of $\epsilon_{Al_{0.8}Ga_{0.2}As}$ with the temperature dependence of the material's bandgap energy, E_g , but no compelling measurements of E_g with temperature exist for Al_{0.8}Ga_{0.2}As. The same can be said for the temperature dependence of the F in Al_{0.8}Ga_{0.2}As. We hope to report measurements of these parameters in future publications.

It is interesting to note that the data reported here can be used to extend Fig. 13 of Ref. 20 to show that plotting the electron-hole pair creation energies for Ge, Si, GaAs (and now Al_{0.8}Ga_{0.2}As) against their respective bandgap energies at 300 K yields a straight line ($\epsilon = 1.5453E_g + 1.8548$ [eV]) with a remarkably good fit ($R^2 > 0.99$) (Fig. 2). A similar plot for a more extensive range of materials is given by Owens and Peacock²² which shows the normally identified "main" ($\epsilon = (14/5)E_g + 0.6$ [eV]) and "secondary" Klein branches. However, it is not clear that all the data plotted in the Owens and Peacock figure are at the same temperature. If they are not, this would necessarily affect any conclusions drawn from that data collection. In either case, it is clear that the Klein function explanation^{22,23} for the relationship between electron-hole pair creation energy and bandgap energy is currently unsatisfactory.²² With regard to

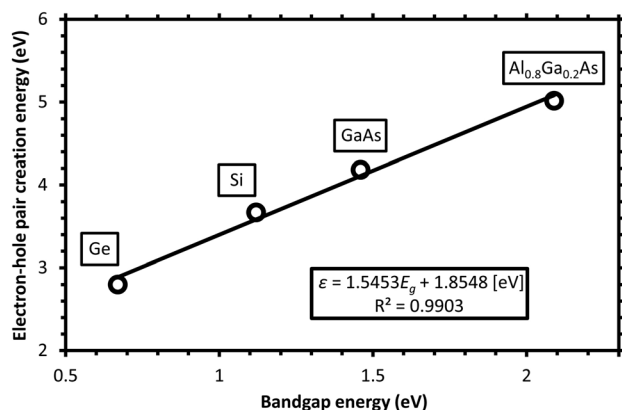


FIG. 2. Electron-hole pair creation energies for Ge, Si, GaAs, and Al_{0.8}Ga_{0.2}As plotted with their respective bandgap energies at 300 K.

developing a revised theory of the relationship between bandgap and electron-hole pair creation energy, it may be illuminating to study the Al_xGa_{1-x}As system with varying x , in order to map in detail the dependence of electron-hole pair creation energy with bandgap across the range from GaAs to AlAs. We hope to be able to make and report these measurements in future.

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